Current and power spectrum in a magnetic tunnel device with an atomic size spacer

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Current and its noise in a ferromagnetic double tunnel barrier device with a small spacer particle were studied in the framework of the sequential tunneling approach. Analytical formulae were derived for electron tunneling through the spacer particle containing only a single energy level. It was shown that Coulomb interactions of electrons with a different spin orientation lead to an increase of the tunnel magnetoresistance. Interactions can also be responsible for the negative differential resistance. A current noise study showed, which relaxation processes can enhance or reduce fluctuations leading either to a super-Poissonian or a sub-Poissonian shot noise.

75.70.Pa, 73.50.Td, 73.23.Hk, 73.40.Gk

I. INTRODUCTION

Recent interest in single-electron tunneling in ferromagnetic double tunnel junctions is stimulated by expected potential applications at microelectronics and by new phenomena observed in such systems.[1,2] In order to have a device operating at room temperature the single electron charging energy $E_c = e^2/2C$ should be much larger than the thermal energy $k_B T$. It can be achieved decreasing the capacitance C of the metallic spacer, which is proportional to its size. In a small metallic spacer a discreteness of the energy spectrum can be relevant and a separation of energy levels $\Delta E \approx k_B T$. Such the situation was studied numerically just recently.[3]

In the present paper we would like to investigate sequential tunneling in an extreme case, when the spacer particle has only a single electron level available for the tunneling process. This simplified model gives us possibility to gain a better insight into spin dependent tunneling processes and to solve the problem analytically. We will show that Coulomb interactions between electrons with different spins can lead to new effects. In some circumstances due to the Coulomb blockade effect the device can operate as a diode, in others it can show the negative differential resistance (NDR). The power spectrum analysis will be performed to understand correlations between currents for electrons of different spins and the transition from the sub-Poissonian to the super-Poissonian current noise in the ferromagnetic device.

II. MODEL AND GENERAL DERIVATIONS

Let us specify the system considered in detail. The separation between the ferromagnetic metallic electrodes is large and therefore, there is no direct electron tunneling between them. The electronic transport can be only via electronic states of the spacer particle placed between the electrodes. The particle can be a molecule (e.g. C_{60}), or a semiconductor quantum dot, in which the relevant energies are $\Delta E, E_c \gg k_B T$. For a small applied voltage V ($eV \ll \Delta E, E_c$) electronic transport is only through a single electronic level E_0. Such the model was considered for a nonmagnetic device in Ref.[4–6] and we generalize it for a ferromagnetic case including tunneling channels for electrons with opposite spin directions. The tunneling process for an electron with spin σ through the left ($j = 1$) and the right ($j = 2$) junction is described by the net tunneling rates $\gamma_{j\sigma}$, which are assumed to be small $\hbar\gamma_{j\sigma} \ll k_B T$. This relation implies that the corresponding tunnel resistances $R_{j\sigma}$ are much larger than the quantum resistance $R_Q = h/2e^2$ and electronic transport can be described within the sequential tunneling approach.[8,4–6] Since ΔE is large, the tunneling process can be considered elastic (there is no thermalization of electrons on the spacer particle, which was usually assumed in the single electron transistor with a large metallic grain)[8,3]. We also neglect fluctuations of the position of the electronic level E_0, which can be caused by thermal and electrostatic fluctuations of the environment.

Our model seems to be familiar to that considered recently for the Kondo effect in quantum dots.[7] A condition for a development of the Kondo resonance is a buildup of many-body correlations between the dot and the electrodes, which can be achieved when electronic waves are coherently scattered on a magnetic impurity. It is in contrast to the present situation, where coupling between the particle and the electrodes is weak and electron tunneling events are uncorrelated and incoherent.

A. Stationary currents

Electronic transport is governed by the master equation

$$\frac{d}{dt}\begin{bmatrix} p_\uparrow \\ p_\downarrow \\ p_0 \end{bmatrix} = \hat{M}\begin{bmatrix} p_\uparrow \\ p_\downarrow \\ p_0 \end{bmatrix} \ , \tag{1}$$

where $p_\uparrow$ and $p_\downarrow$ denotes the probability to find an electron with the spin $\sigma =\uparrow$ and $\downarrow$, p_0 - the probability for an empty state E_0. Of course, the total probability $p_\uparrow + p_\downarrow + p_0 = 1$. The matrix $\hat{M}$ is given by

$$\hat{M} = \begin{bmatrix} -\Gamma_\uparrow^- & 0 & \Gamma_\uparrow^+ \\ 0 & -\Gamma_\downarrow^- & \Gamma_\downarrow^+ \\ \Gamma_\uparrow^- & \Gamma_\downarrow^- & -\Gamma_\uparrow^+ - \Gamma_\downarrow^+ \end{bmatrix} \ , \tag{2}$$

where $\Gamma_\sigma^\pm = \Gamma_{1\sigma}^\pm + \Gamma_{2\sigma}^\pm$, $\Gamma_{j\sigma}^\pm = f_j^\pm \gamma_{j\sigma}$ are the total tunneling rates to (+) and off (−) the particle level E_0, $f_j^\pm = \{1 + \exp[\pm(E_0 - E_F - (-1)^j eV_j)/k_BT]\}^{-1}$. The voltage V is applied to the left electrode and the voltage drop across the left and the right junction is $V_1 = C_2V/C$ and $V_2 = C_1V/C$, respectively. Here, C_j denotes the capacitance of the j-th tunnel junction and $C = C_1 + C_2$.

At the stationary state the probability p_σ and p_0 are determined from the master equation (1) with the left hand side equal to zero, and the result is

$$p_\sigma = \frac{\Gamma_\sigma^+\Gamma_{-\sigma}^-}{\gamma_\uparrow\gamma_\downarrow - \Gamma_\uparrow^+\Gamma_\downarrow^+} \ , \quad p_0 = \frac{\Gamma_\uparrow^-\Gamma_\downarrow^-}{\gamma_\uparrow\gamma_\downarrow - \Gamma_\uparrow^+\Gamma_\downarrow^+} \ , \tag{3}$$

where $\gamma_\sigma = \gamma_{1\sigma} + \gamma_{2\sigma}$. The current through the left junction for electrons with the spin σ is the difference of the tunneling current flowing to (+) and from (−) the particle

$$\begin{aligned} I_{1\sigma} \equiv I_{1\sigma}^+ - I_{1\sigma}^- &= -e\left[\Gamma_{1\sigma}^+ p_0 - \Gamma_{1\sigma}^- p_\sigma\right] \\ &= -e(f_1^+ - f_2^+)\frac{\gamma_{1\sigma}^+\gamma_{2\sigma}^+\Gamma_{-\sigma}^-}{\gamma_\uparrow\gamma_\downarrow - \Gamma_\uparrow^+\Gamma_\downarrow^+} \ . \end{aligned} \tag{4}$$

Since there are no electronic relaxation processes on the particle, it results from the current conservation rule that $I_{1\sigma} = I_{2\sigma}$ for each electronic channel.

In magnetic tunnel junctions the resistance depends on the relative configuration of magnetic moments in the electrodes and this effect is known as the tunnel magnetoresistance (TMR). The value of TMR is given by the ratio $TMR = (I_P - I_{AP})/I_{AP}$, where I_P and I_{AP} are the tunneling currents in the parallel (P) and the antiparallel (AP) configuration of the magnetic moments in the electrodes. It is convenient to express the tunneling rate coefficients in the form $\gamma_{1\sigma} = \gamma_0(1 \pm P_1)$ and $\gamma_{2\sigma} = \gamma_0\alpha(1 \pm P_2)$, where the sign + (−) corresponds to the spin $\sigma =\uparrow (\downarrow)$, P_1 and P_2 is the magnetic polarization of the left and the right electrode, α denotes the asymmetry between the potential barriers. Using Eq.(4) one gets

$$TMR = \frac{(1 - f_1^+ f_2^+)4\alpha P_1P_2}{(1+\alpha)^2 - (P_1 + \alpha P_2)^2 - (f_1^+ + \alpha f_2^+)^2 + (P_1 f_1^+ + \alpha f_2^+ P_2)^2} \ . \tag{5}$$

For comparison we present the results for noninteracting electrons, i.e when the single electron charging energy $E_c = 0$. In this limit the double occupancy of the level E_0 is allowed. The current through the left junctions for electrons with the spin σ is then

$$I_{1\sigma}^0 = -e(f_1^+ - f_2^+)\frac{\gamma_{1\sigma}\gamma_{2\sigma}}{\gamma_\sigma} \tag{6}$$

and TMR

$$TMR^0 = \frac{4\alpha P_1P_2}{(1+\alpha)^2 - (P_1 + \alpha P_2)^2} \ . \tag{7}$$

Comparison of both the expressions for TMR [Eq.(5) and (7)] shows that Coulomb interactions can significantly increase the value of the magnetoresistance.

B. Fluctuations

Fluctuations in the system are studied within the generation-recombination approach for multi-electron channels.[9,10,3] The Fourier transform of the correlation function of the quantity X can be expressed as[9,10]

$$S_{XX}(\omega) \equiv 2\int_{-\infty}^{\infty} dt e^{i\omega t}\left[\langle X(t)X(0)\rangle - \langle X\rangle^2\right]$$
$$= 4\sum_{n,m} X_n\left[P(n,m;\omega) - \frac{p_n}{i\omega}\right]X_m p_m, \tag{8}$$

where p_m is the stationary value of the probability $\hat{p}$ at the state m [given by Eq.(3)], X_m is the value of X at this state. The conditional probability $P(n,m;t)$ to find the system in the state n at time t, if it was in the initial state m at $t=0$, satisfies the master equation (1),[9,10] and its Fourier transform is given by $P(n,m;\omega) = [i\omega - \hat{M}]^{-1}_{nm}$. The elements of the Green's function $G(n,m;\omega) \equiv [i\omega - \hat{M}]^{-1}_{nm} - p_n/i\omega$ can be determined directly by matrix inversion and the result is

$$\hat{G}(\omega) = \frac{\hat{A}^+}{i\omega - \lambda_+} - \frac{\hat{A}^-}{i\omega - \lambda_-}\ , \tag{9}$$

where $\lambda_\pm = (-\gamma_\uparrow - \gamma_\downarrow \pm \Delta)/2$ are the nonzero eigenvalues of the matrix $\hat{M}$, $\Delta = \sqrt{(\gamma_\uparrow - \gamma_\downarrow)^2 + 4\Gamma^+_\uparrow\Gamma^+_\downarrow}$,

$$\hat{A}^r = \frac{1}{D}\begin{bmatrix} \Gamma^-_\uparrow a^r_{\uparrow,\uparrow} & \Gamma^+_\uparrow a^r_{\uparrow,\downarrow} & \Gamma^+_\uparrow a^r_{\uparrow,0} \\ \Gamma^-_\downarrow a^r_{\downarrow,\uparrow} & \Gamma^+_\downarrow a^r_{\downarrow,\downarrow} & \Gamma^+_\downarrow a^r_{\downarrow,0} \\ \Gamma^-_\uparrow a^r_{\uparrow,0} & \Gamma^-_\downarrow a^r_{\downarrow,0} & -\Gamma^+_\uparrow a^r_{\uparrow,0} - \Gamma^+_\downarrow a^r_{\downarrow,0} \end{bmatrix} \tag{10}$$

corresponding to λ_r ($r=\pm$), $a^r_{\sigma,\sigma} = \lambda_r\gamma_{-\sigma} + \gamma^2_{-\sigma} + \Gamma^+_\uparrow\Gamma^+_\downarrow$, $a^r_{\sigma,-\sigma} = -\Gamma^-_{-\sigma}(\lambda_r + \gamma_\uparrow + \gamma_\downarrow)$, $a^r_{\sigma,0} = -(\lambda_r + \gamma_{-\sigma})\Gamma^-_{-\sigma} + \Gamma^+_{-\sigma}\Gamma^-_\sigma$, and $D = \Delta(\gamma_\uparrow\gamma_\downarrow - \Gamma^+_\uparrow\Gamma^+_\downarrow)$. The Green's function (9) is not singular for $\omega \to 0$ and therefore, one can easily separate the amplitudes of the noise resulting from fluctuation processes characterized by the relaxation time $\tau_r = -1/\lambda_r$.

The fluctuations of the charge and the spin are expressed as

$$S_{NN}(\omega) = 4e^2\sum_{\sigma,\sigma'} G_{\sigma\sigma'}(\omega)p_{\sigma'} =$$
$$\frac{4e^2\Gamma^-_\uparrow\Gamma^-_\downarrow}{\Delta(\gamma_\uparrow\gamma_\downarrow - \Gamma^+_\uparrow\Gamma^+_\downarrow)^2}\sum_{\sigma,r} r\frac{\Gamma^+_{-\sigma}\Gamma^-_\sigma(\lambda_r + \Gamma^-_\sigma)}{i\omega - \lambda_r}\ , \tag{11}$$

$$S_{MM}(\omega) = 4\frac{\mu_B^2}{4}\sum_{\sigma,\sigma'} \sigma\sigma' G_{\sigma\sigma'}(\omega)p_{\sigma'} =$$
$$\frac{\mu_B^2\Gamma^-_\uparrow\Gamma^-_\downarrow}{\Delta(\gamma_\uparrow\gamma_\downarrow - \Gamma^+_\uparrow\Gamma^+_\downarrow)^2}\sum_{\sigma,r} r\frac{\Gamma^+_{-\sigma}(\gamma_\sigma + \Gamma^+_\sigma)(\lambda_r + \gamma_\sigma + \Gamma^+_\sigma)}{i\omega - \lambda_r}\ , \tag{12}$$

where μ_B is the Bohr magneton.

The correlations between the currents $I_{j\sigma}$ and $I_{j'\sigma'}$ in the tunnel junction j and j' for the electrons with the spin σ and σ' are described by the power spectrum[10]

$$S_{I_{j\sigma}I_{j'\sigma'}}(\omega) = \delta_{jj'}\delta_{\sigma\sigma'}S^{Sch}_{j\sigma} + S^c_{I_{j\sigma}I_{j'\sigma'}}(\omega)\ , \tag{13}$$

where

$$S^{Sch}_{j\sigma} \equiv -2e(I^+_{j\sigma} + I^-_{j\sigma}) = 2e^2\left[\Gamma^+_{j\sigma}p_0 + \Gamma^-_{j\sigma}p_\sigma\right] \tag{14}$$

is the high frequency ($\omega \to \infty$) limit of the shot-noise (the Schottky noise), which is the sum of the components corresponding to the tunneling current flowing to and from the particle. The frequency dependent part is expressed as[10]

$$S^c_{I_{j\sigma}I_{j'\sigma'}}(\omega) = 2e^2(-1)^{j-j'}\{[\Gamma^+_{j\sigma}G_{0\sigma'}(\omega) - \Gamma^-_{j\sigma}G_{\sigma\sigma'}(\omega)]\Gamma^+_{j'\sigma'}p_0 + [\Gamma^+_{j'\sigma'}G_{0\sigma}(-\omega) - \Gamma^-_{j'\sigma'}G_{\sigma'\sigma}(-\omega)]\Gamma^+_{j\sigma}p_0$$
$$+[\Gamma^-_{j\sigma}G_{\sigma 0}(\omega) - \Gamma^+_{j\sigma}G_{00}(\omega)]\Gamma^-_{j'\sigma'}p_{\sigma'} + [\Gamma^-_{j'\sigma'}G_{\sigma' 0}(-\omega) - \Gamma^+_{j'\sigma'}G_{00}(-\omega)]\Gamma^-_{j\sigma}p_{\sigma}\} \ . \tag{15}$$

The shot noise of the total current (including the displacement currents as well) is given by

$$S_{II} = \sum_{j,j'} \frac{C_1^2 C_2^2}{C^2 C_j C_{j'}} \sum_{\sigma,\sigma'} [\delta_{jj'}\delta_{\sigma\sigma'} S^{Sch}_{j\sigma} + S^c_{I_{j\sigma}I_{j'\sigma'}}(\omega)] \ . \tag{16}$$

III. RESULTS

The analysis of the results we begin from a simplified situation, when the electrodes are made of paramagnetic metals. Next the device with ferromagnetic electrodes is considered. Since Coulomb interactions break the electron-hole symmetry, one can expect that the characteristics of the device for $E_0 < E_F$ are different from those for $E_0 > E_F$. Therefore, the both situations are considered separately.

A. Paramagnetic case

In the system with paramagnetic electrodes both the channels for electrons with the spin $\uparrow$ and $\downarrow$ are equivalent and the tunneling rates $\gamma_{j\uparrow} = \gamma_{j\downarrow} = \gamma_j$, $\gamma_\uparrow = \gamma_\downarrow = \gamma$, $\Gamma^\pm_\uparrow = \Gamma^\pm_\downarrow = \Gamma^\pm$. The total current $I_1 = -2e(f_1^+ - f_2^+)\gamma_1\gamma_2/[\gamma + \Gamma^+]$ differs form that for noninteracting electrons by the factor Γ^+ in the denominator, which results form Coulomb interactions. In low temperatures there is a current blockade for the voltage within the range $-C/C_2 < eV/(E_0 - E_F) < C/C_1$. Dynamics of the fluctuations are characterized by the eigenvalues $\lambda_+ = -\gamma + \Gamma^+$ and $\lambda_- = -\gamma - \Gamma^+$. Using Eqs.(13)-(15) and (9)-(10) one can derive the correlation function between the currents for electrons with the same spin as

$$S_{I_{1\uparrow}I_{1\uparrow}}(\omega) = 2e^2\frac{\gamma_1(f_1^+\Gamma^- + f_1^-\Gamma^+)}{\gamma + \Gamma^+}$$
$$-2e^2\frac{\gamma_1^2}{\gamma+\Gamma^+}\left[\frac{f_1^+f_1^-(\Gamma^-)^2}{\omega^2+\lambda_+^2} - \frac{a_-}{\omega^2+\lambda_-^2}\right] \tag{17}$$

and between the different spins

$$S_{I_{1\uparrow}I_{1\downarrow}}(\omega) = 2e^2\frac{\gamma_1^2}{\gamma+\Gamma^+}\left[\frac{f_1^+f_1^-(\Gamma^-)^2}{\omega^2+\lambda_+^2} + \frac{a_-}{\omega^2+\lambda_-^2}\right] \ , \tag{18}$$

where $a_- = (1+f_1^+)[f_1^+(\Gamma^{+2} + 2\gamma\Gamma^+ - \gamma^2) - 2(\Gamma^+)^2]$. Thus, the power spectrum of the total current through the left junction is expressed by

$$S_{I_1I_1}(\omega) = 4e^2\frac{\gamma_1(f_1^+\Gamma^- + f_1^-\Gamma^+)}{\gamma+\Gamma^+}$$
$$+8e^2\frac{\gamma_1^2}{\gamma+\Gamma^+}\frac{a_-}{\omega^2+\lambda_-^2} \ . \tag{19}$$

The noise corresponding to the eigenvalue λ_+ is completely cancelled. In the high-voltage regime the above formulae are much simpler, e.g. for $V > 0$ the current[4] $I_1 = 2e\gamma_1\gamma_2/(\gamma_1 + 2\gamma_2)$ and the Fano factor[5]

$$\mathcal{F}_{11} \equiv \frac{S_{I_1I_1}(\omega=0)}{2eI_1} = 1 - \frac{4\gamma_1\gamma_2}{(\gamma_1+2\gamma_2)^2} \ . \tag{20}$$

(see also [11] and references therein).

For comparison in the case of noninteracting electrons ($E_c = 0$) there are two independent channels and the power spectrum can be written as

$$S^0_{I^0_{1\sigma}I^0_{1\sigma}}(\omega) = 2e^2\frac{\gamma_{1\sigma}[f_1^+\Gamma^-_\sigma + f_1^-\Gamma^+_\sigma]}{\gamma_\sigma} -4e^2\frac{\gamma^2_{1\sigma}[f_1^+(\Gamma^-_\sigma)^2 + f_1^-(\Gamma^+_\sigma)^2]}{\gamma_\sigma(\omega^2+\gamma^2_\sigma)} \tag{21}$$

for electrons with spin σ. For the paramagnetic electrodes and in the limit of a large positive V one gets [from Eqs.(6) and (21)] the total current $I_1^0 = 2e\gamma_1\gamma_2/(\gamma_1+\gamma_2)$ and the Fano factor $\mathcal{F}^0_{11} = 1 - 2\gamma_1\gamma_2/(\gamma_1+\gamma_2)^2$.[11]

Let us present also the correlation function between the currents through different tunnel junctions

$$\mathrm{Re}[S_{I_1I_2}(\omega)] = 4e^2\frac{\gamma_1\gamma_2}{\gamma+\Gamma^+}\frac{b_{12}}{\omega^2+\lambda^2_-}\ , \tag{22}$$

where $b_{12} = \Gamma^{+2}(4 + f_1^+ + f_2^+ - 2f_1^+f_2^+) + (f_1^+ + f_2^+ + 2f_1^+f_2^+)(\Gamma^- - \Gamma^+)\gamma$. Now, using Eq.(16) one gets the total power spectrum of the device

$$S_{II}(\omega) = 4e^2\frac{(C_2^2\gamma_1f_1^+ + C_1^2\gamma_2f_2^+)\Gamma^- + (C_2^2\gamma_1f_1^- + C_1^2\gamma_2f_2^-)\Gamma^+}{C^2(\gamma+\Gamma^+)} +8e^2\frac{\Gamma^2_{12}(\Gamma^{+2}+2\gamma\Gamma^+-\gamma^2) - \Gamma_{12}\gamma_{12}\Gamma^{-2} - 2\gamma^2_{12}\Gamma^{+2}}{(\gamma+\Gamma^+)(\omega^2+\lambda^2_-)}\ , \tag{23}$$

where $\Gamma_{12} = (C_2\gamma_1f_1^+ - C_1\gamma_2f_2^+)/C$, $\gamma_{12} = (C_2\gamma_1 - C_1\gamma_2)/C$. One can check that in the zero-frequency limit $S_{I_1I_1}(0) =\mathrm{Re}[S_{I_1I_2}(0)] = S_{I_2I_2}(0)$. Therefore, the Fano factors $\mathcal{F}_{11} = \mathcal{F}_{12} = \mathcal{F}_{22}$, which in the high-voltage range can be simply expressed as $\mathcal{F} = 1 - 4\gamma_1\gamma_2/(\gamma_1+2\gamma_2)^2$.

We are also interested in charge and spin fluctuation induced by the flowing current. Using the formula (11) and (12) for the paramagnetic device one can write the charge-charge and the spin-spin correlation function as

$$S_{NN}(\omega) = \frac{8e^2\Gamma^+\Gamma^-}{(\gamma+\Gamma^+)(\omega^2+\lambda^2_-)} \tag{24}$$

$$S_{MM}(\omega) = \frac{2\mu_B^2\Gamma^+\Gamma^-}{(\gamma+\Gamma^+)(\omega^2+\lambda^2_+)}\ . \tag{25}$$

From a frequency dependence of the correlation functions S_{NN} and S_{MM} one can assign the relaxation time corresponding to the charge and the spin fluctuations as $\tau_{charge} = -1/\lambda_-$ and $\tau_{spin} = -1/\lambda_+$, respectively. One can check that the same result for the correlation functions can be derived from the two-level generation-recombination approach[9] using $S_{XX}(\omega) = 4\mathrm{var}(X)\tau/(\omega^2\tau^2+1)$, where $\mathrm{var}(X) = \langle X^2\rangle - \langle X\rangle^2$ is the variance of the quantity X. Since $\tau_{spin} > \tau_{charge}$ then spin fluctuations occur in a low frequency regime, while the charge fluctuations in higher frequencies. The amplitude of the spin noise $S_{MM}(\omega=0)$ is larger than $S_{NN}(\omega=0)$ (in some cases the difference can be a few orders of magnitudes[3]). In the paramagnetic system the spin fluctuations, however, do not contribute to the current shot noise. The frequency dependence of the power spectrum (19) has then a Lorentzian form with the relaxation time τ_{charge}.

B. Ferromagnetic electrodes and $E_0 < E_F$

Let us first consider the ferromagnetic double tunnel barrier device, in which the particle level is below the Fermi level of the electrodes. A typical voltage dependence of the current is shown in Fig.1a. The I-V function has a step like shape, with the current blockade for small voltages [in the range $-C/C_1 < eV/(E_F - E_0) < C/C_2$] and the plateaux in the limit of large voltages, in which

$$I_1 = \begin{cases} e\frac{\gamma_{1\uparrow}\gamma_{1\downarrow}(\gamma_{2\uparrow}+\gamma_{2\downarrow})}{\gamma_\uparrow\gamma_\downarrow-\gamma_{2\uparrow}\gamma_{2\downarrow}} & \text{for} \quad V \gg (E_F-E_0)/e, \\ -e\frac{\gamma_{2\uparrow}\gamma_{2\downarrow}(\gamma_{1\uparrow}+\gamma_{1\downarrow})}{\gamma_\uparrow\gamma_\downarrow-\gamma_{1\uparrow}\gamma_{1\downarrow}} & \text{for} \quad V \ll -(E_F-E_0)/e. \end{cases} \tag{26}$$

We remind that according to our assumptions $|V| \ll \Delta E, E_c$ and the tunneling rates $\gamma_{j\sigma}$ are independent of V, even for the so called *high voltages* when the currents are given by Eq.(26). The current intensities (26) for large positive and negative voltages are different, in contrast to the case of noninteracting electrons, where both the I-V steps are equal. Fig.1a shows that the height of the steps depends on the magnetic asymmetry of the electrodes, and an increase

of the magnetic polarization P_1 in the left electrode reduces the current for $V > 0$. If this electrode is made of a half-metallic ferromagnet (i.e. for $P_1 = 1$ and $\gamma_{1\downarrow} = 0$) the conducting channel corresponds only to electrons with the spin $\uparrow$, and there is the Coulomb blockade $I_1 = 0$ in low temperatures ($k_B T \ll (E_F - E_0)$) for any positive voltage. An electron with the spin $\downarrow$, which has tunneled form the right electrode into the particle, is captured there forever. The electron can neither tunnel to the left nor to the right electrode, and blocks the conducting channel for electrons with the spin $\uparrow$. Electronic transport can only occur for large negative voltages. Such the device works as a diode.

Using Eq.(26) one finds

$$TMR = \frac{4\alpha P_1 P_2}{1 - P_1^2 + 2\alpha - 2\alpha P_1 P_2} \tag{27}$$

in the limit $V \gg (E_F - E_0)/e$. For comparison the value for noninteracting electrons

$$TMR^0 = \frac{4\alpha P_1 P_2}{1 - P_1^2 + 2\alpha - 2\alpha P_1 P_2 + \alpha^2(1 - P_2^2)} \;, \tag{28}$$

is much smaller, especially in the system with asymmetric tunnel junctions ($\alpha \gg 1$). One can say that Coulomb interactions enhance the value of TMR.

The power spectrum on the conducting step (for $V > 0$) is given by

$$S_{I_1 I_1}(\omega) = 2e^2 \frac{\gamma_{1\uparrow}\gamma_{1\downarrow}(\gamma_{2\uparrow} + \gamma_{2\downarrow})}{\gamma_\uparrow \gamma_\downarrow - \gamma_{2\uparrow}\gamma_{2\downarrow}} - \frac{4e^2 \gamma_{1\uparrow}\gamma_{1\downarrow}(\gamma_{2\uparrow} + \gamma_{2\downarrow})}{\Delta(\gamma_\uparrow \gamma_\downarrow - \gamma_{2\uparrow}\gamma_{2\downarrow})^2} \sum_r r\lambda_r \frac{\lambda_r a + b}{\omega^2 + \lambda_r^2} \tag{29}$$

where $a = -\gamma_{1\uparrow}\gamma_{1\downarrow}(\gamma_{2\uparrow} + \gamma_{2\downarrow})$ and $b = \gamma_{1\uparrow}^2 \gamma_{2\downarrow}(\gamma_{2\uparrow} - \gamma_{1\downarrow}) + \gamma_{1\downarrow}^2 \gamma_{2\uparrow}(\gamma_{2\downarrow} - \gamma_{1\uparrow}) - 2\gamma_{1\uparrow}\gamma_{1\downarrow}\gamma_{2\uparrow}\gamma_{2\downarrow}$. The eigenvalue in this case is $\lambda_r = (-\gamma_\uparrow - \gamma_\downarrow + r\Delta)/2$, and $\Delta = \sqrt{(\gamma_\uparrow - \gamma_\downarrow)^2 + 4\gamma_{2\uparrow}\gamma_{2\downarrow}}$. The voltage dependence of the Fano factor is presented in Fig.1b. One can show that the zero-frequency power spectrum $S_{I_j I_{j'}}(\omega = 0)$ corresponding to the currents through different tunnel junctions are equal, and thus, the Fano factors $\mathcal{F}_{11} = \mathcal{F}_{12} = \mathcal{F}_{22}$ for any model parameters (for any transition rates $\gamma_{j\sigma}$ at any voltage). In the regime of high-voltage its value is $\mathcal{F} = 1 + 2b/(\gamma_\uparrow \gamma_\downarrow - \gamma_{2\uparrow}\gamma_{2\downarrow})^2$. If the coefficient b is negative, then $\mathcal{F} < 1$ and the noise is of the sub-Poissonian type. It occurs for $2\alpha P_1^2(1 - P_2^2) < (1 - P_1 P_2)(1 - P_1^2)$. The transition from the sub-Poissonian to the super-Poissonian type of the current shot noise is a continuous process. In order to understand it we plotted in Fig.2 the frequency dependent part of the correlation functions $S^c_{I_{1\sigma} I_{1\sigma'}}(\omega = 0)$ [given by Eq.(15)] for the currents of electrons with different spins through the left junction in the high-voltage limit. One can expect competition between tunneling processes for electrons with the spin $\uparrow$ and $\downarrow$, which leads to an enhancement of the current noise. For simplicity the right electrode is taken paramagnetic, i.e. the source electrode can emit electrons with the same transition rate ($\gamma_{2\uparrow} = \gamma_{2\downarrow}$). The drain electrode is ferromagnetic and therefore, there is an asymmetry between the out-going channels for electrons with opposite spin directions, which is described by the magnetic polarization P_1. For $P_1 = 0$, the functions are equal $S^c_{I_{1\uparrow} I_{1\uparrow}}(0) = S^c_{I_{1\downarrow} I_{1\downarrow}}(0) = S^c_{I_{1\uparrow} I_{1\downarrow}}(0)$ and negative. It means that all tunneling events are anti-correlated, which leads to a reduction of the noise. An increase of the polarization P_1 increases the tunneling rate $\gamma_{1\uparrow}$ for electrons with the spin $\uparrow$, they can faster leave the particle. Electrons with the opposite spin ($\downarrow$) spend a long time on the particle. It effects in the spin accumulation,[2] which is responsible for an increase of $S^c_{I_{1\uparrow} I_{1\uparrow}}(0)$ and $S^c_{I_{1\uparrow} I_{1\downarrow}}(0)$. Their values can cross zero and achieve maxima for $P_1 \to 1$. The function $S^c_{I_{1\downarrow} I_{1\downarrow}}(0)$ is always negative (for $P_1 > 0$). The process results an enhancement of the shot noise and the transition to the super-Poissonian range. The maximum value of the Fano factor $\mathcal{F} = 1 + 2\gamma_{2\uparrow}/\gamma_{1\downarrow}$ occurs for the left electrode made of a half-metallic ferromagnet ($P_1 = 1$). Fig.2 shows also that a large asymmetry factor $\alpha \gg 1$ between the left and the right tunnel barrier can prefer the transition to the super-Poissonian shot noise (see the dashed curves corresponding to $\alpha = 10$).

C. Ferromagnetic electrodes and $E_0 > E_F$

In the case of $E_0 > E_F$ one can expect similar characteristics of our device to those presented above for $E_0 < E_F$. It is really the case, but only for the high-voltage regime, where the *I-V* curve has plateaux, whose level is given by Eq.(26). Fig.3 presents the voltage dependence of the current and the Fano factor. (Since the curves in the range of negative V are very similar to those from Fig.1, we present the dependences for $V > 0$ only). It is seen a resonant-like peak of the current in the range of moderate voltages, at $E_0 - eV_2 \approx E_F$ (i.e. for $V/(|E_0 - E_F|/e) \approx 2$ in Fig.3a).

Its height can be much above the plateau level in the device with large asymmetry of the tunnel junctions. The most pronounced peak is for the device with the left electrode made of a half-metallic ferromagnet ($P_1 = 1$, $\gamma_{1\downarrow} = 0$). The total current, in this case, can be written as

$$I_{1\uparrow} = e\frac{(f_1^+ - f_2^+)f_2^- \gamma_{1\uparrow}\gamma_{2\uparrow}}{(1 - f_1^+ f_2^+)\gamma_{1\uparrow} + (1 - f_2^{+2})\gamma_{2\uparrow}} \ . \tag{30}$$

It is worth noticing, that in this limit the current (30) and the occupation probability $p_\uparrow$, $p_\downarrow$, p_0 are independent of the transition rate $\gamma_{2\downarrow}$. The current peak is the resonant-like transition of electrons through the particle level and the current blockade effect in the low and the high-voltage range. For a small V the position of the particle level $E_0 - eV_2$ is above the Fermi level E_F of the right electrode and electrons can not tunnel to the particle, whereas in a high-voltage range there is a Coulomb blockade of the conducting channel by an electron with spin $\downarrow$ captured on the particle. The width of the current peak depends on the smearing of the Fermi surface and decreases with a decreasing temperature.

The I-V curve (30) resembles that obtained in the case of resonant tunneling through double barrier in semiconductors (the Esaki diode).[12] The nature of the both tunneling effects is, however, different. In the present case the negative differential resistance (NDR) is caused by Coulomb interactions between electrons on the particle (by the Coulomb blockade effect). In the Esaki diode[12] the charge accumulation in the well is irrelevant for electronic transport and the NDR results from a shift of the conduction band of the source electrode out of the resonant tunneling range (see [13–17,11], which considered coulomb interactions in resonant tunneling as well). The width of the peak depends in the Esaki diode on the electronic structure of the device. It can be smeared due to fluctuations of the bottom of the potential well.[17,11] In our model the position of E_0 is fixed and the broadening of the peak results only from the thermal distribution of electrons around the Fermi level.

Fig.3b shows the voltage dependence of the Fano factor. Its value is below unity in the low-voltage range and rapidly increases when $E_0 - eV_2$ crosses the Fermi level E_F (i.e. for $V/(|E_0 - E_F|/e) > 2$ in Fig.3b). The increase of $\mathcal{F}$ is only in a narrow range of V, in the same in which the NDR effect is observed. In the high-voltage regime the noise is super-Poissonian for the most situations exhibited in Fig.3b. The voltage dependence of the Fano factor in the present case (see the curve for $P_1 = 1$ in Fig.3b) is qualitatively different from that in the resonant tunneling diode[14–16], where $\mathcal{F}$ shows a large peak in the NDR region. The origin of the Fano peak is activation of interaction-induced fluctuations of the band bottom in the quantum well, when the system passes to the off-resonant electronic transport.[15–17,11] As we have explained already in the previous section, the high value of $\mathcal{F}$ in our system is related with the asymmetry of the conducting channels for electrons with the opposite spin directions.

Flowing electrons induce the charge and the spin fluctuations on the particle with the characteristic frequencies $1/\tau_{charge} = -\lambda_-$ and $1/\tau_{spin} = -\lambda_+$, respectively. These fluctuations should be seen in the current noise. Therefore, we separate the Schottky term S_I^{Sch} from the current noise and perform the spectral decomposition of the frequency dependent part $S_{II}^c(\omega)$. The total power spectrum can be expressed as

$$S_{II}(\omega) = S_I^{Sch} + S_{II}^{c+}(\omega) + S_{II}^{c-}(\omega) \ , \tag{31}$$

where $S_I^{Sch} = (C_2^2 S_{I1}^{Sch} + C_1^2 S_{I2}^{Sch})/C^2$ and

$$S_{II}^{c\pm}(\omega) = \pm\left(\frac{C_1C_2}{C}\right)^2 \sum_{j,j'} \frac{\lambda_\pm}{C_jC_{j'}} \frac{\lambda_\pm a_{jj'} + b_{jj'}}{\omega^2 + \lambda_\pm^2} \ . \tag{32}$$

The coefficient $a_{jj'}$ and $b_{jj'}$ are determined from Eq.(15), (9), (10) and (3). The voltage dependences of these terms for $\omega = 0$ are presented in Fig.4. The system is the same as studied above (Fig.3), in which the asymmetry between the tunnel barriers is $\alpha = 10$. The transition rates $\gamma_{2\sigma}$ are larger than $\gamma_{1\sigma}$, and therefore $S_{I2}^{Sch} > S_{I1}^{Sch}$. In the low-voltage range the term S_{I2}^{Sch} is very large and dominates in S_I^{Sch}. The Fano factor $\mathcal{F} = [S_I^{Sch} + S_{II}^{c+}(0) + S_{II}^{c-}(0)]/(2eI)$ is, however, below unity. In the considered system we change the magnetic polarization P_1, which influences of S_{I1}^{Sch}, but it is irrelevant for S_I^{Sch}. It explains, why all the curves in Fig.4a are so close to each other.

Fig.4b and 4c show the terms $S_{II}^{c+}(0)$ and $S_{II}^{c-}(0)$ corresponding to the contribution of the spin and the charge fluctuations to the current noise. They are negative in the low-voltage range and positive for larger voltages. This indicates a change of current correlations when the particle level crosses the Fermi level ($E_0 - eV_2 \approx E_F$). The value $S_{II}^{c+}(0)$ strongly increases with an increase of the magnetic polarization P_1. Since S_{II}^{c-} and S_I^{Sch} (see Fig.4c and 4a) are weakly dependent on P_1, it is evident that S_{II}^{c+} is responsible for an enhancement of the Fano factor. Frequency dependent measurements of the current noise can confirm our prediction, that low frequency fluctuations dominate in the super-Poissonian noise in ferromagnetic tunnel junctions.

IV. SUMMARY

Summarizing, our sequential tunneling studies, performed in the ferromagnetic double barrier device with the atomic size particle, showed a few interesting effects. First, Coulomb interactions lead to an enhancement of the TMR effect. Second, an electron-hole symmetry is broken in the system, due to Coulomb interactions. The characteristics of the ferromagnetic device, with the electronic state E_0 of the spacer particle below the Fermi level E_F of the electrodes, are qualitatively different from those for the case of $E_0 > E_F$. We showed that the system, in which $E_0 < E_F$ and one electrode is made of a half-metallic ferromagnet, can operate as a diode. When $E_0 > E_F$ the device showed the NDR effect, which is better pronounced for ferromagnetic electrodes with different magnetic polarizations. Third, the transition from the sub-Poissonian to the super-Poissonian current noise is a continuous process, which depends on the magnetic asymmetry between the tunneling channels for electrons with the spin ↑ and ↓. The asymmetry between the left and the right tunnel barrier can facilitate the transition to the super-Poissonian range. Spin fluctuations are relevant for the super-Poissonian current noise and they are activated in the Coulomb blockade regime. The charge fluctuations are responsible for the sub-Poissonian current noise. The spin and the charge fluctuations have distinct relaxation times $\tau_{spin} > \tau_{charge}$, which can be observed in frequency dependent measurements of the power spectrum in a low and in a high-frequency range, respectively.

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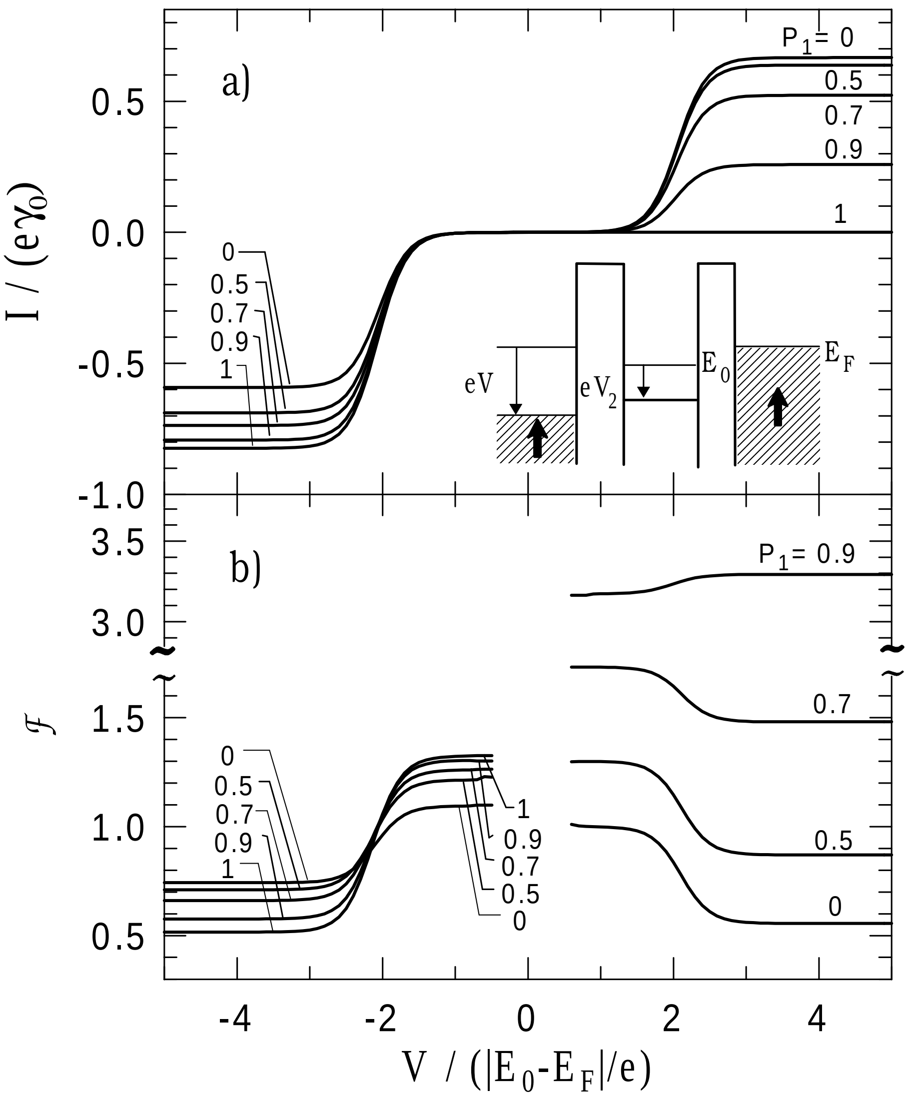

FIG. 1. Voltage dependence of the current (a) and the Fano factor (b) in the ferromagnetic double barrier with the resonating level $E_0 < E_F$ for different magnetic polarizations of the left electrode $P_1 = 0$, 0.5, 0.7, 0.9, 1. The polarization of the right electrode is $P_2 = 0.4$, the asymmetry between the barrier $\alpha = 1$, the capacitances $C_1 = C_2$, the difference $|E_F - E_0|/e$ is taken as unity, and the temperature $T = 0.1$. The inset shows the scheme of the electronic structure.

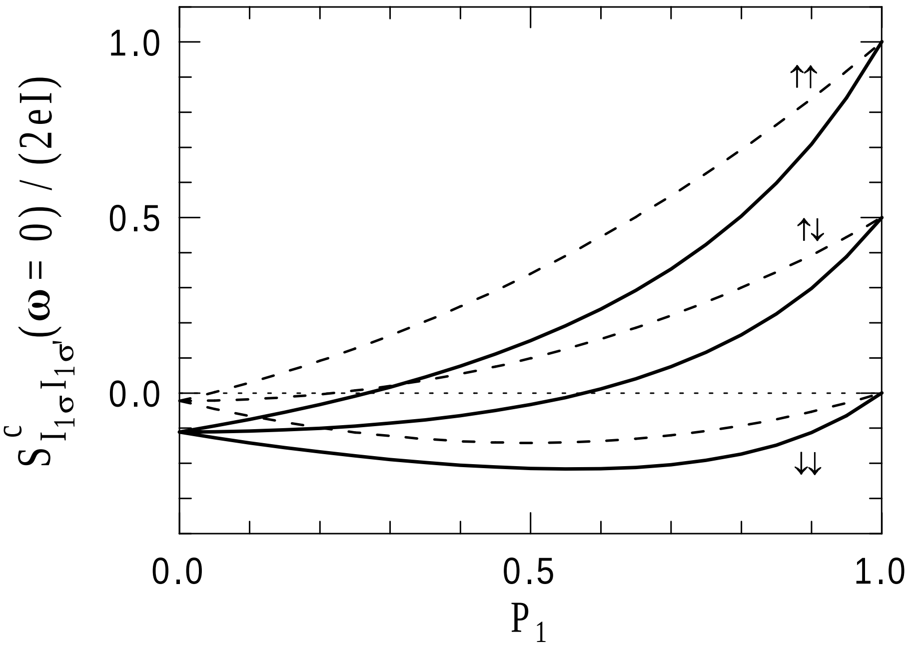

FIG. 2. The frequency dependent part of the correlation functions $S^c_{I_{1\uparrow}I_{1\uparrow}}$, $S^c_{I_{1\downarrow}I_{1\downarrow}}$ and $S^c_{I_{1\uparrow}I_{1\downarrow}}$ at $\omega = 0$ for the currents with different spin orientation as a function of the magnetic polarization P_1 in the left electrode. The plot was done for the currents in the high-voltage limit and for the device with the right paramagnetic electrode ($P_2 = 0$), the asymmetry between the tunnel barriers is taken as $\alpha = 1$ (solid curves) and $\alpha = 10$ (dashed curves).

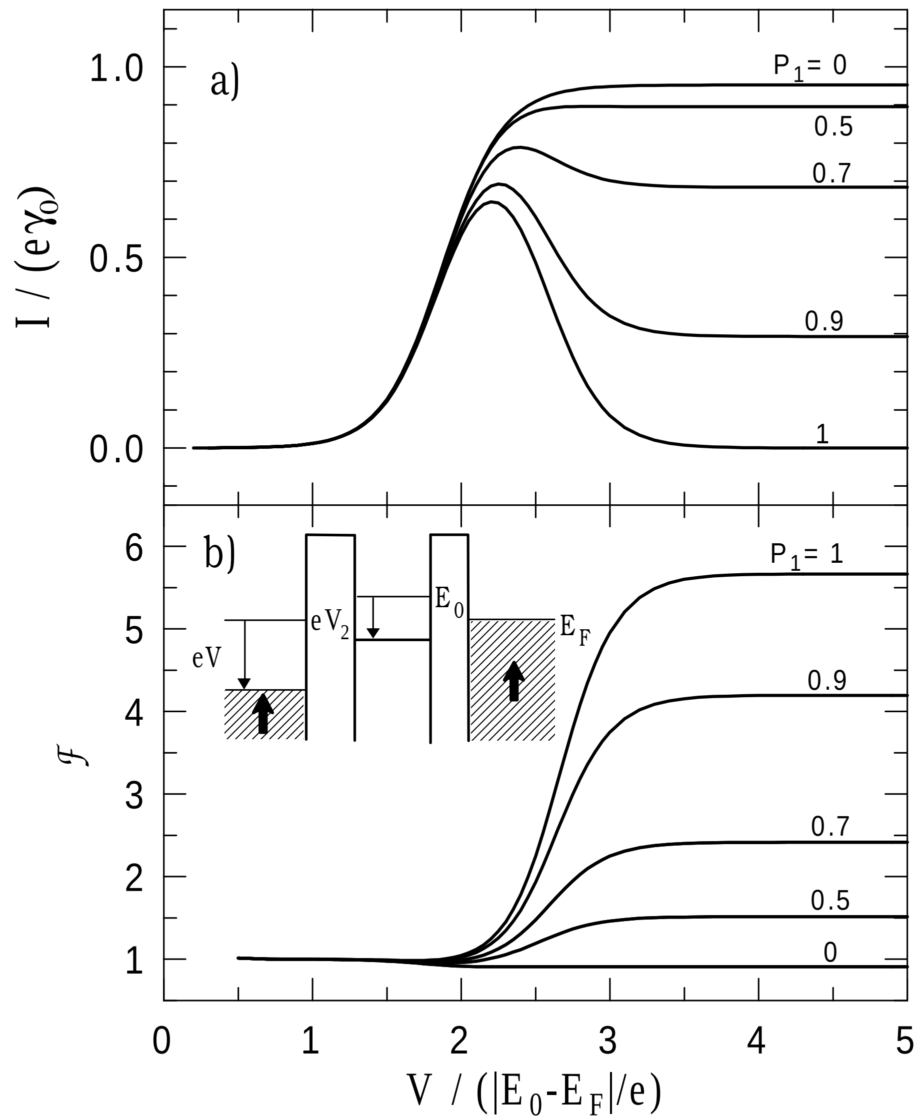

FIG. 3. Voltage dependence of the current (a) and the Fano factor (b) in the ferromagnetic double barrier with the resonating level $E_0 > E_F$ for different magnetic polarizations of the left electrode $P_1 = 0$, 0.5, 0.7, 0.9, 1. The polarization of the right electrode is $P_2 = 0.4$, the asymmetry between the barrier $\alpha = 10$, the capacitances $C_1 = C_2$, the difference $|E_F - E_0|/e$ is taken as unity, and the temperature $T = 0.1$. The inset shows the scheme of the electronic structure for this case.

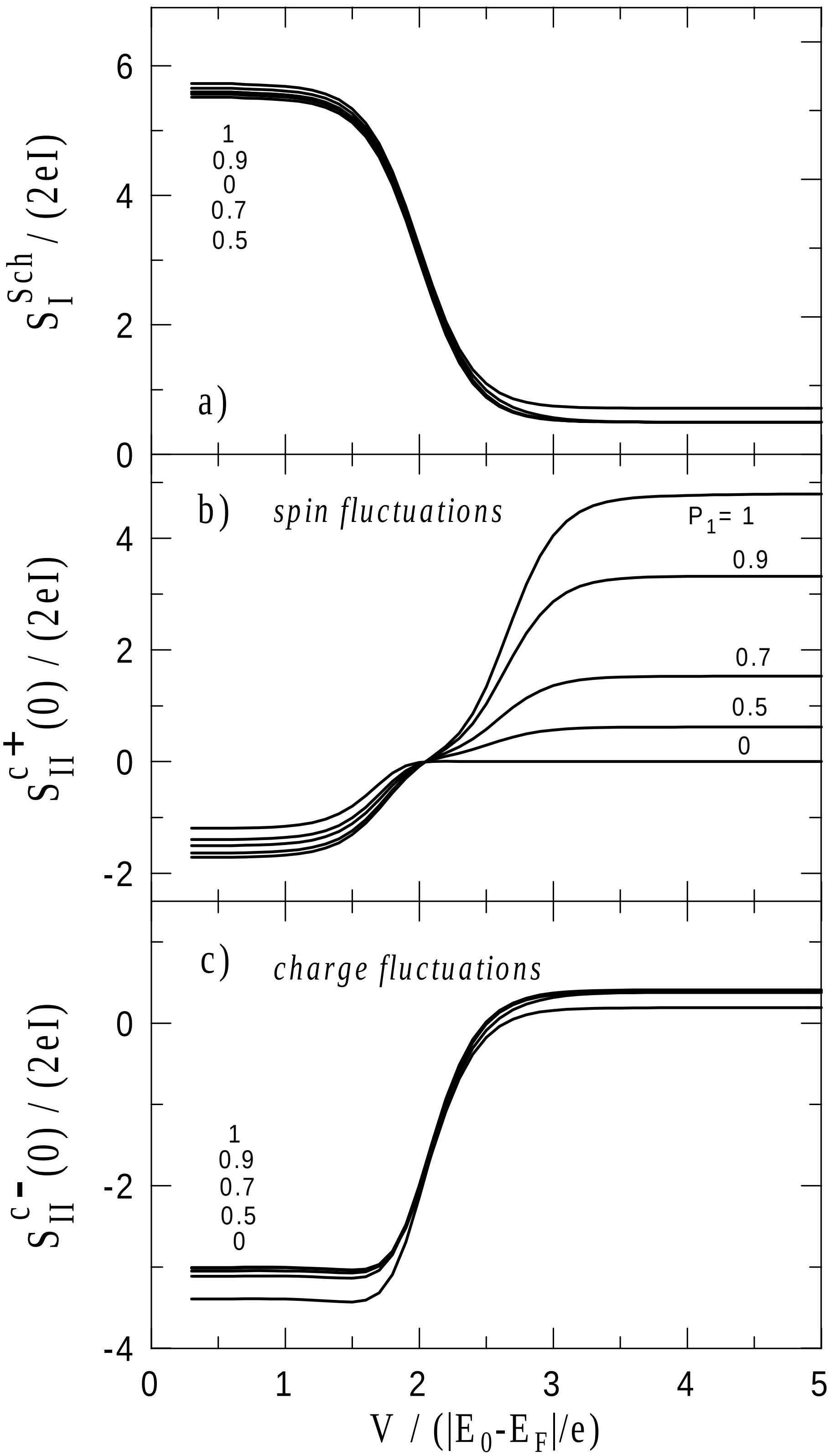

FIG. 4. Voltage dependence of the different components of the zero-frequency current noise: the Schottky term (a), the frequency dependent parts S_{II}^{c+} and S_{II}^{c-} corresponding to the relaxation time $\tau_{spin} = -1/\lambda_+$ (b) and $\tau_{charge} = -1/\lambda_-$ (c), respectively. The plots are done for the ferromagnetic device the same as in Fig.3 with the magnetic polarization of the left electrode $P_1 = 0$, 0.5, 0.7, 0.9, 1.